

Is there potential complementarity between LISA and pulsar timing?

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Abstract. We open the discussion into how the Laser Interferometer Space Antenna (LISA) observations of supermassive black-hole (SMBH) mergers (in the mass range $\sim 10^6 - 10^8 M_\odot$) may be complementary to pulsar timing-based gravitational wave searches. We consider the toy model of determining pulsar distances by exploiting the fact that LISA SMBH inspiral observations can place tight parameter constraints on the signal present in pulsar timing observations. We also suggest, as a future path of research, the use of LISA ring-down observations from the most massive (\gtrsim a few $10^7 M_\odot$) black-hole mergers, for which the inspiral stage will lie outside the LISA band, as both a trigger and constraint on searches within pulsar timing data for the inspiral stage of the merger.

1. Introduction

A major source of strong gravitational wave (GW) signals for the future space-based GW detector LISA [1, 2] will be the inspiral and ring-down of merging supermassive black-holes (SMBHs) at cosmological distances (e.g [3].) The primary sensitive frequency band for LISA is 0.0001–0.1 Hz and the most abundant SMBH mergers in this range will have component masses in the $10^4 - 10^6 M_\odot$ range. Inspirals can potentially be seen for SMBH systems with masses up to a few $10^7 M_\odot$, although at greater masses than this the frequency at which they reach their last stable orbit and merge will be outside the sensitive LISA band (i.e. $\lesssim 10^{-4}$ Hz.) More massive systems up to a few $10^8 M_\odot$ merge before they enter the LISA frequency band, but are observable in their ring-down phase [3], with characteristic frequency given by $f_c \approx 1.3 \times 10^{-3} (10^7 M_\odot / M)$ Hz (where M is the post-coalescence black-hole mass.) Such systems will potentially be observed at signal-to-noise ratios of hundreds to thousands allowing their waveform to be precisely parameterised. Estimates of event rates vary greatly between authors (see [4] for a summary of estimates), but could range from tens to thousands of events over a range of distances and signal-to-noise ratios.

With pulsar timing there is another method to observe low frequency GWs. This requires stable millisecond pulsars with low intrinsic noise and very accurate pulsar timing models [5, 6] to produce timing residuals that could contain a GW signal. Current experiments (e.g. the Parkes Pulsar Timing Array - PPTA [7]), with sample rates of order two weeks or so, are sensitive to GWs with frequencies $\lesssim 10^{-6}$ Hz. However, in the future with the Square Kilometre Array (SKA) daily sampling may be possible giving an upper limit on frequencies of $\lesssim 10^{-5}$ Hz. For

the higher mass SMBH systems ($\gtrsim 10^7 M_\odot$) these frequencies would have been swept through thousands of years prior to the final stage inspiral observed by LISA, but pulsars, at distances of several kiloparsecs and therefore affected by the past GW signal from when the pulsar’s pulses were emitted, may contain signals at these low frequencies. This suggests that there may be some overlap or complementarity between the two types of observation which could be exploited to gain the maximum astrophysical information.

The ideas presented here can be compared to previous work [8, 9] in which upper limits on potential nearby SMBH binaries were placed using pulsar timing. In those studies assumptions about the sources, based on some, maybe speculative, observational evidence were used to constrain the system models and produce upper limits on the system parameters. Here we suggest using LISA observations as the constraint on the models with which we search in pulsar timing data. The non-observation of inspirals in both LISA and pulsar timing from known recently merged galaxies would place limits on SMBH systems at different stages of the binary evolution or with different mass ranges.

2. Pulsar timing

Many pulsars are very precise clocks. The residuals in their timing, after the removal of an observationally-fitted model of the pulsar’s phase evolution, are a potential probe of the low frequency GW spectrum [10]. Residuals contain noise from signal processing and the intrinsic instability of the pulsar. The PPTA [7] aims to time tens of the most stable pulsars with precisions of around 100 ns. In the future with the SKA it may be possible to time thousands of millisecond pulsars, some of which with a precision of < 100 ns [11]. There have already been efforts to search for a GW background [12], and individual systems [9], of SMBH inspirals in existing pulsar timing data.

Pulsar timing residuals contain two components of a gravitational wave signal: the part passing the Earth (which will be correlated between all pulsar observations); and the part passing the pulsar as it emitted the pulses now being observed. The residual amplitude from the signal will depend on (other than the intrinsic GW strain) the angular separation between the GW source and the pulsar, with sources along the pulsar line-of-sight producing no residual. The timing residual amplitude will also increase with the source period. An example of the pre-fit timing residuals that would remain in the timing of a perfectly modeled pulsar ~ 3 kpc away, due to the inspiral of two $5 \times 10^9 M_\odot$ SMBHs¹, can be seen in Figure 1. The low frequency component of the residual from the signal passing the pulsar can easily be distinguished from the high frequency component as the signal passes the Earth. Pulsar timing residuals observed before the SMBH merger is seen in LISA would contain both components of the signal, although the high frequency component would likely be too high to be observed, but pulsar observations after the event is seen in LISA would only contain the low frequency (i.e. at the pulsar) component.

LISA is expected to be launched within the next 10–15 years, with a similar timescale to the proposed development of the SKA, meaning there could be overlap between their operation. On these timescales the pulsar community hope to be timing many pulsars with ~ 100 ns (or less) precision. However, overlap between these two experiments is not necessary for complementarity to exist between LISA and pulsar timing, as archive pulsar timing data could be looked at once LISA observations have been made, or vice versa. Thus even current pulsar timing data sets could be useful, and would indeed give a longer time baseline of data to study in the future.

3. Pulsar distance measurements

First we will discuss a toy model showing one way in which LISA observations and pulsar timing could be complementary under a set of extremely optimistic assumptions: a method of pulsar

¹ This system would be outside the LISA band, but is used for ease of visualisation.

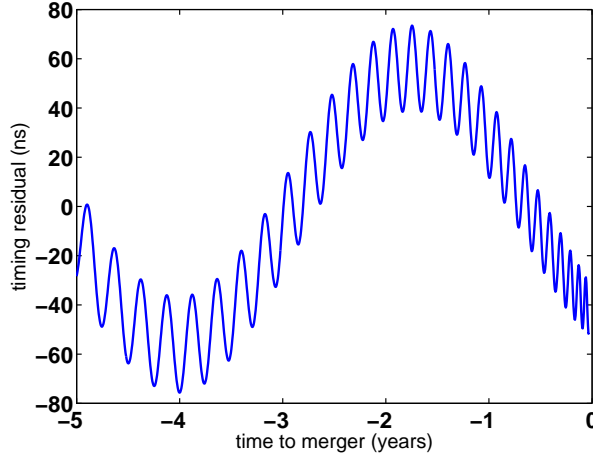


Figure 1. The residual left in the timing of a pulsar at a distance of ~ 3 kpc, with an angular separation between the source and the pulsar of $\pi/2$ rads, caused by the coalescence of two $5 \times 10^9 M_\odot$ black holes at a distance of 1 Gpc.

distance determination. This application is more for use as a way of opening up discussion into other areas of complementarity than for its real world applicability.

For the high signal-to-noise ratio inspirals seen with LISA the parameters describing the signal, including the source sky location, can be very well constrained. Consequently the equivalent waveform present in the pulsar timing data can be approximated such that the only unknown is the distance to the pulsar. This provides a way of obtaining pulsar distances, for the stable millisecond pulsars used in GW searches at least, independently of the galactic electron density distribution model [14] used in dispersion measure distance estimates, which can have large uncertainties [15]. However, for such pulsars high precision measurements of parallax or the orbital period derivative have, and will in the future, be used to give extremely precise distance measurements with errors of order $\sim \pm 1\%$ (see e.g. [16, 17].) Here we will see if our method can be competitive with these other methods.

We create five years of data prior to a LISA observed merger, consisting of 500 equally spaced observations, containing a signal from a simulated system of two black holes with redshifted masses of $5 \times 10^7 M_\odot$ at $z = 1$. This kind of system would be just within the LISA sensitive band before merger. We consider a pulsar with an angular separation of 45° from the SMBH binary, at a distance of ~ 3 kpc, and, to estimate the limiting potential of this method, firstly subject to a highly *unrealistic* timing residual noise² of around 0.02 ns (note that expected residuals will be of order 10–100 ns.) In this case the pulsar distance can be determined to about 1–2% accuracy (see Figure 2.) However, if the residual noise becomes just a few times larger the distance estimation will substantially degrade. To obtain pulsar distances with a few percent error (e.g. comparable to those in [16]), using the potentially obtainable timing residuals of 100 ns (with the PPTA) up to 10 ns [18] would require the SMBH system to be ~ 0.5 and ~ 5 Mpc away respectively. Such high mass ($\gtrsim 5 \times 10^7 M_\odot$) inspirals within these distance ranges are extremely rare (see [19] for predictions of event rates) and lower mass systems would need to be even closer to give decent pulsar distance estimates. From this study it can be seen that the orbital period derivative and parallax methods show far better promise as a realisable

² This residual noise is Gaussian and white and not representative of real world residuals in either its amplitude or spectral shape.

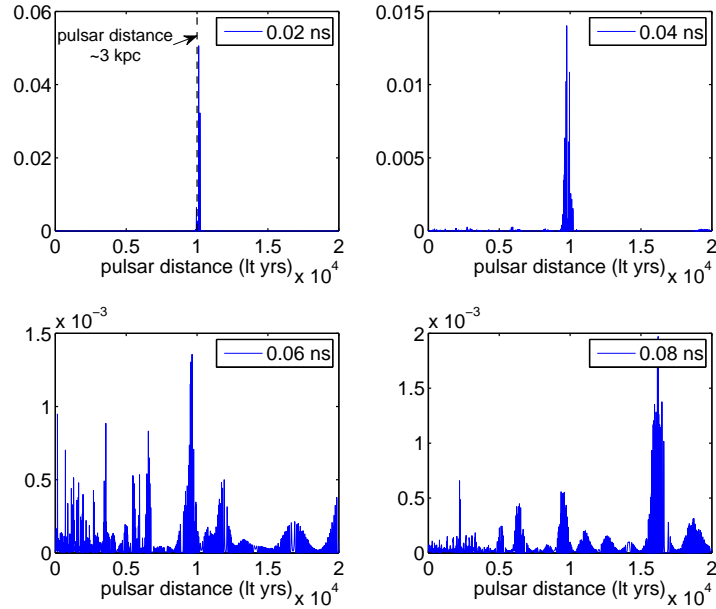


Figure 2. The probability distribution of the pulsar distance calculated using simulated timing residual data containing an injected inspiral signal from two $5 \times 10^7 M_\odot$ black holes at $z = 1$ and Gaussian white noise with standard deviations of 0.02, 0.04, 0.06 and 0.08 ns.

and accurate pulsar distance measurement than our method.

4. Ring-down signals as triggers

The ring-down of the SMBH formed after mergers offers a better LISA detection rate for high mass systems (greater than a few $10^7 M_\odot$), due to their higher signal frequency and visibility to larger distances [3]. However, LISA will be unable to obtain information about the inspiral phase for these systems. Pulsar timing observations might, then, provide an opportunity to probe this unseen inspiral stage of the merger. Some constraints on the system parameter space and the time of coalescence seen by LISA will yield a trigger with which to search in pulsar timing data. Current pulsar distance estimates could be used to aid the search. Unfortunately the ring-down does not provide information on the source’s sky position making the parameter space more complicated, although there may be other electromagnetic counterparts to the signal that could give the source position. Preliminary work suggests that to see any of the SMBH ring-downs that occur at a reasonable rate within the LISA band (i.e. are at cosmological distances), would be impossible with any single pulsar observations using current and projected achievable timing residuals. However, if we consider the fact that observations of multiple pulsars will be made (potentially hundreds to thousands of separate objects with the SKA) then a global fit using data from them all will help dig into the noise and could reveal a signal. Multiple pulsar observations could also be used to estimate the source position. This work will be discussed more thoroughly in a future paper.

5. Conclusions

With the advent of dedicated pulsar timing of the most stable pulsars direct GW detection via measurements of their timing residuals may soon be possible. There are certain events which

could overlap between being observed in the planned space-based GW detector LISA (or even more distant future space-based detectors) and the pulsar timing data. We have suggested some ways in which such measurements could be complementary and reveal astrophysics that would be more difficult, or unobtainable, with one alone. Using current, and near term projected, pulsar timing accuracies, the measurement of pulsar distances as described above would require a very serendipitous event. The reconstruction of the inspiral, for events only observed as ring-downs in LISA, again would likely require more very stable pulsars observations and a serendipitous loud, nearby merger. This area of investigation is intended for further study and will hopefully reveal other areas of complementarity.

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